The Navy Layered Ocean Model Users Guide

Prepared for Ocean Sensing and Prediction Division
Ocean Science Directorate
Contract # N00014-89-C-6002

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*Formerly NORDA Report 251

Foreword

Efficient and robust ocean models are an essential component of any ocean prediction system. The ocean model described here is part of several prediction products currently under evaluation by the Navy. In conjunction with this report, the source code for the ocean model is being made available to the ocean modeling community. The Naval Oceanographic and Atmospheric Research Laboratory hopes that it will be joined by other ocean models to form a community resource library, as recommended by the recent Workshop on Ocean Prediction.

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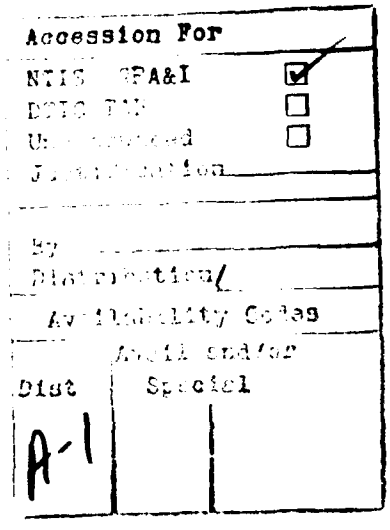
Executive Summary

This report is a users guide to the Navy's hydrodynamic (isopycnal) nonlinear, primitive equation, layered ocean circulation model. The model retains the free surface and uses a semi-implicit time scheme that treats all gravity waves implicitly. It can handle full-scale bottom topography, provided it is confined to the lowest layer, and an arbitrary coastline geometry.

The model has been in use at the Naval Oceanographic and Atmospheric Research Laboratory for more than 10 years for simulations of the ocean circulation in the Gulf of Mexico, the Caribbean Sea, the Alboran Sea, the western Mediterranean Sea, and the global oceans. In conjunction with the issuance of this report, the model code is being made available to the ocean modeling community.

The vertically integrated equations of motion and their finite difference discretization on a C-grid is presented, as is a description on the semi-implicit time scheme, the boundary conditions, and the external forcing.

The model code contains internal documentation that fully describes the user-specified model parameters and data sets. This report also contains general information about how to use the model, in particular, how to set it up for a new ocean region and how to port it to a new computer system.



Acknowledgments

This work was funded by the Naval Air Development Center, Program Element 0602435N. George Heburn, Harley Hurlburt, Dana Thompson, and many other past and present members of NOARL's Ocean Dynamics and Prediction Branch contributed to the development of the ocean model described in this report.

The mention of commercial products or the use of company names does not in any way imply endorsement by the U.S. Navy or NOARL.

Contents

The Navy Layered Ocean Model Users Guide

1.0 Introduction

The layered ocean circulation model has been under development since 1976 by the Naval Oceanographic and Atmospheric Research Laboratory (NOARL). The original version, written by Hurlburt and Thompson (1980), was a one- or two-layer finite depth, or one-active-layer reduced-gravity, hydrodynamic primitive equation ocean model on a beta-plane. This version retained the free surface and used a semi-implicit time scheme, was formulated on the C-grid, and could handle only rectangular or simple nonrectangular regions. The Helmholtz equations from the semi-implicit scheme were solved using a version of the Hockney (1965) method, as implemented by Moore (1989). The capacitance matrix technique (Buzbee et al., 1971) was used for nonrectangular regions.

The model was first used at NOARL in a major study of the Gulf of Mexico (Hurlburt and Thompson, 1980; 1982), and a description of the model as it then existed was included as an appendix to the 1980 paper. Since that time the capability of the model has been greatly expanded and the computer code completely rewritten. Hurlburt and Thompson (1980) remain the appropriate refereed reference on the basic model design. Their article includes many details that will not be repeated here and should be used in addition to this report.

The major features of the Navy layered ocean circulation model are listed.

- Layers in the vertical.
- Nonlinear primitive equations.
- Free surface.
- Semi-implicit time scheme.
- Hydrodynamic, i.e., isopycnal.
- Full-scale bottom topography in lowest layer.
- Arbitrary coastline geometry

Upgrades to the original model include the following.

- The model region can be any closed geometry; i.e., any coastline resolvable by the grid spacing can be used. There is no limit on the number of islands in the region.
- The model grid is uniform, but it can be on a beta-plane, on an f-plane, or on the surface of an earth-sized sphere. The spherical geometry version was formulated by Heburn (NOARL, personal communication).
- The model can have any number of layers.
- The external mode Helmholtz equation from the semi-implicit time scheme is solved by a standard FORTRAN 77 package that uses a fast direct solver for rectangular regions (Swarztrauber, 1977) and the capacitance matrix technique for nonrectangular regions. Moore (1989) wrote the fast Fourier transform component of the fast direct solver.

• The internal mode Helmholtz equations are solved by a standard FORTRAN 77 implementation of the red-black successive over-relaxation iterative scheme (Hageman and Young, 1981).

• Versions of the reduced gravity models that use an explicit time step are available.

• Open outflow boundaries now use a variant of the Orlanski (1976) radiation condition, developed by Heburn (1986).

• Any number of open-boundary sections can be placed along any zonal or meridional sections of "coastline," and each layer can have its own set of open boundary sections.

• "Hydromixing" may be used to control the surfacing of layer interfaces, using a formulation by Thompson and Wallcraft (personal communication). It is identical to mixing in a thermodynamic layered model, except that layer density is not changed.

The model has been optimized to study and predict mesoscale oceanic features over relatively large regions. It has been used at NOARL to study the ocean circulation of the following regions.

• The Gulf of Mexico at grid resolutions of 0.2° and 0.1° (Hurlburt and Thompson, 1980 and 1982; Hurlburt, 1984 and 1986; Hurlburt et al., 1990; Kindle, 1986; Thompson, 1986; Wallcraft, 1985 and 1986).

• The Caribbean (Heburn et al., 1982; Kinder et al., 1985).

• The Alboran Sea (Preller and Hurlburt, 1982; Parrilla et al., 1986; Preller, 1986).

• The Western Mediterranean at 7.5 by 5 km (Heburn, 1986 and 1988; Heburn and La Violette, 1990).

• The Gulf Stream region at 0.2° and 0.125° resolution (Hurlburt and Thompson, 1984; Thompson and Schmitz, 1989).

• The Indian Ocean at 0.4° (Kindle and Thompson, 1989).

• The Pacific north of 20°S at 0.25° and 0.125° (Hurlburt et al., 1991).

• The global ocean at 0.5° resolution (Hurlburt et al., 1989; Kindle et al., 1989; Murray et al., 1989 and 1990).

Layers are an efficient way of modeling the ocean's vertical structure. Successful simulations are possible with two or three appropriately located Lagrangian layers, while at least 20 vertical levels are typically used in level model simulations (Semtner and Chervin, 1988). Moreover, the model's semi-implicit time scheme treats all gravity waves implicitly, which allows a longer time step than primitive equation models that use a rigid lid or time splitting. The difference in time step depends on the region being simulated, but typically the semi-implicit time step is three times longer than that required by schemes that treat internal gravity waves explicitly. The model is therefore at least 100 times more efficient, in terms of central processing time, than existing level-type primitive equation ocean models with 20 or more levels, and it also requires significantly less computer memory. The major disadvantage of this layer formulation is that bottom topography is confined to the lowest layer, which makes the model less useful in coastal regions. However, it has proved quite successful at modeling seamounts, e.g., the effect of the New England seamount chain on the Gulf Stream (Hurlburt and Thompson, 1984).

2.0 Model Formulation

2.1 Model Equations

The vertically integrated equations of motion used in the n-layer finite depth hydrodynamic model are, for $k = 1. \ . \ . \ .n$:

$$\frac{\partial \vec{V}_k}{\partial t} + (\nabla \cdot \vec{V}_k + \vec{V}_k \cdot \nabla)\vec{v}_k + \hat{k} \times f\vec{V}_k =$$

$$- h_k \sum_{l=1}^{n} G_{kl} \nabla (h_l - H_l)$$

$$+ \max(0, \omega_k)\vec{v}_{k+1} - (\max(0, -\omega_k) + \max(0, \omega_{k-1}))\vec{v}_k$$

$$+ \max(0, -\omega_{k-1})\vec{v}_{k-1}$$

$$+ \left(\vec{\tau}_{k-1} - \vec{\tau}_k\right)/\rho_o + A_H h_k \nabla^2 \vec{v}_k$$

$$\frac{\partial h_k}{\partial t} + \nabla \cdot \vec{V}_k = \omega_k - \omega_{k-1} \qquad (1)$$

where

h_k = k-th layer thickness;

$\vec{v}_k$ = k-th layer velocity;

$\vec{V}_k$ = $h_k \vec{v}_k$;

H_k = k-th layer thickness at rest;

$H_n = D(x, y) - \sum_{l=1}^{n-1} H_l$;

$D(n, y)$ = total ocean depth at rest;

ρ_k = k-th layer density, constant in space and time;

$$G_{kl} = \begin{cases} g & \text{for } l \le k \\ g - g(\rho_l - \rho_k)/\rho_o & \text{for } l > k; \end{cases}$$

f = Coriolis parameter;

A_H = coefficient at horizontal eddy viscosity;

C_k = coefficient of interfacal friction;

C_b = coefficient of bottom friction;

$\vec{\tau}_w$ = wind stress;

$$\vec{\tau}_k = \begin{cases} \vec{\tau}_w & \text{for } k = 0 \\ C_k \rho_o |\vec{v}_k - \vec{v}_{k+1}| (\vec{v}_k - \vec{v}_{k+1}) & \text{for } k = 1 \ . \ . \ . \ n-1 \\ C_b \rho_o |\vec{v}_n| \vec{v}_n & \text{for } k = n; \end{cases}$$

$$\omega_k = \begin{cases} 0 & \text{for } k = 0, \ n \\ \max(0, \omega_k^+) - \max(0, \omega_k^-) - h_k \widehat{\omega}_k & \text{for } k = 1 \ . \ . \ . \ n-1; \end{cases}$$

$$\omega_k^+ = \widetilde{\omega}_k \frac{h_k^+}{4}\left(\frac{1}{h_k} - \frac{1}{h_k^+}\right);$$

$$\omega_k^- = \tilde{\omega}_k \frac{h_k^+}{4}\left(\frac{1}{h_k^- + h_k^+ - h_k} - \frac{1}{h_k^+}\right);$$

$$\hat{\omega}_k = \frac{\iint(\max(0,\omega_k^+) - \max(0,\omega_k^-))}{\iint H_k};$$

$\tilde{\omega}_k$ = k-th interface reference vertical mixing velocity;

h_k^+ = k-th layer thickness at which entrainment starts; and

h_k^- = k-th layer thickness at which detrainment starts.

This layered formulation, with transports $\vec{V}$ as dependent variables, handles strongly sloping topography especially well, as long as it is confined to the lowest layer. The bottom topography appears multiplicatively in the pressure gradient term, and is differentiated only to the extent that it affects the velocity field in the advective terms. When large-amplitude topography is introduced, restrictions on the time step and the eddy coefficient are affected only to the extent that the topography determines the amplitude of the velocity field. The continuity equation is linear when written in transport form, thus avoiding complications from the nonlinear advective term when layer thickness and velocity are used as variables.

The surfacing of layer interfaces has always been a problem for layer models. The traditional solution has been to make each layer sufficiently thick to prevent the problem from occurring. However, this practice often leads to a vertical structure that is not in line with that of the ocean region under study. The hydrodynamic model is an isopycnal model (the density is constant in space and time for each layer); however, hydromixing has been included to prevent surfacing. The physics of hydromixing are identical to mixing in a layered thermodynamic model currently under development at NOARL, except that the fluid entrained from another layer is assumed to be at the same density as the receiving layer. It is primarily designed to prevent any layer interface from surfacing, and depends only on the layer thickness and three user-supplied parameters: a reference vertical mixing velocity, $\tilde{\omega}_k$; a layer thickness at which to start entrainment, h_k^+; and a layer thickness at which to start detrainment, h_k^-.

In practice explicit detrainment is often deactivated by making h_k^- very deep. Mixing has been formulated to involve no net transfer of fluid between layers, so if there is local entrainment it will be balanced by region-wide detrainment. This global mixing balance term, $\hat{\omega}_k$, has been included to allow long-term integrations; however, it is an additional source of damping. For regions with port forcing, the layer thickness can alternately be balanced by adjusting the net transport in or out of the region, thus removing the need for the $\hat{\omega}_k$ term. Hydromixing is a relatively new addition to the ocean model; it significantly expands the range of problems that can be investigated with the model, but it should be used only if the solutions with mixing provide a more realistic simulation than those without mixing.

A hydrodynamic reduced gravity model with n active layers has a lowest layer that is infinitely deep and at rest, i.e., $V_{n+1} = 0$, $h_{n+1} = \infty$,

and $\nabla h_{n+1} = 0$. The model equations for the active layers are identical to those for an n-layer hydrodynamic finite depth model, except that

$$H_n = \text{constant}$$

$$G_{kl} = \begin{cases} g(\rho_{n+1} - \rho_k)/\rho_o & \text{for } l \le k \\ g(\rho_{n+1} - \rho_l)/\rho_o & \text{for } l > k \end{cases}$$

$$\vec{\tau}_k = \begin{cases} \vec{\tau}_\omega & \text{for } k = 0 \\ C_k \rho_o |\vec{v}_k - \vec{v}_{k+1}| (\vec{v}_k - \vec{v}_{k+1}) & \text{for } k = 1 \ldots n \end{cases}$$

and

$$\omega_k = \begin{cases} 0 & \text{for } k = 0 \\ \max(0, \omega_k^+) - \max(0, \omega_k^-) - h_k \hat{\omega}_k & \text{for } k = 1 \ldots n. \end{cases}$$

In general, the reduced gravity model is more robust than the finite depth model, and an $n-1$ active-layer reduced-gravity model can give similar results to an n-layer finite depth model. So it is often cost effective to develop a reduced gravity model of a region first and then go on to a finite depth model.

2.2 Finite Difference Equations

The model equations are solved numerically on a staggered C-grid. For simplicity, the β-plane version is described here. The operators are defined as

$$\delta_{mz}(W(z)) = (m\Delta)^{-1}\left(W\left(z + \frac{m\Delta}{2}\right) - W\left(z - \frac{m\Delta}{2}\right)\right)$$

$$\overline{W(z)}^{mz} = 1/2\left(W\left(z + \frac{m\Delta}{2}\right) + W\left(z - \frac{m\Delta}{2}\right)\right), \qquad (2)$$

where W is a function of the discrete variable z, Δ refers to a space or time increment, and m is an integer assumed to be 1 if omitted. Then the finite difference form of the finite depth hydrodynamic model equations for $k = 1 \ldots n$ is given.

$$\begin{aligned} \delta_{2t} U = &- \delta_x (\bar{U}^x \bar{u}^x) - \delta_y (\bar{V}^x \bar{u}^y) + \overline{(f \bar{v}^y h)}^x \\ &- \bar{h}^x \sum_{l=1}^{n} G_{kl} \delta_x (h_l - H_l) \\ &- \hat{H}_k \sum_{l=1}^{n} G_{kl} \delta_x \left(\overline{(h_l - H_l)}^{2t} - (h_l - H_l)\right) \\ &+ \max(0, \bar{\omega}_k^x) u_{k+1}^{t-\Delta t} - (\max(0, -\bar{\omega}_k^x) + \max(0, \bar{\omega}_{k-1}^x)) u_k^{t-\Delta t} \\ &+ \max(0, -\bar{\omega}_{k-1}^x) u_{k-1}^{t-\Delta t} \\ &+ (\tau_{k-1}^x - \tau_k^x)/\rho_o + A_H \overline{h^{t-\Delta t}}^x (\delta_x \delta_x u^{t-\Delta t} + \delta_y \delta_y u^{t-\Delta t}) \end{aligned} \qquad (3)$$

$$\delta_{2t} V = -\delta_x (\overline{U}^y \overline{v}^x) - \delta_y (\overline{V}^y \overline{v}^y) - \overline{(f \overline{u}^x h)}^y$$

$$- \overline{h}^y \sum_{l=1}^{n} (G_{kl} \delta_y (h_l - H_l)) \qquad (4)$$

$$-\widehat{H}_k \sum_{l=1}^{n} G_{kl} \delta_y \left(\overline{(h_l - H_l)^{2t}} - (h_l - H_l) \right)$$

$$+ \max (0, \overline{\omega}^y_k) v^{t-\Delta t}_{k+1} - (\max (0, -\overline{\omega}^y_k) + \max (0, \overline{\omega}^y_{k-1})) v^{t-\Delta t}_k$$

$$+ \max (0, \overline{\omega}^y_{k-1}) v^{t-\Delta t}_{k-1}$$

$$+ (\tau^y_{k-1} - \tau^y_k)/\rho_o + A_H \overline{h^{t-\Delta t}}^y (\delta_x \delta_x v^{t-\Delta t} + \delta_y \delta_y v^{t-\Delta t}) \qquad (5)$$

$$\delta_{2t} h = -\delta_x (\overline{U}^{2t} - \delta_y \overline{V}^{2t} + \omega_k - \omega_{k-1} \qquad (6)$$

$$\omega = \begin{cases} 0 & \text{for } k = 0,\ n \\ \max (0, \omega^+) - \max (0, \omega^-) - h_k \widehat{\omega} & \text{for } k = 1 \ . \ . \ . \ n-1 \end{cases} \qquad (7)$$

$$\omega^+ = q \frac{h^+}{4} \left(\frac{1}{h^{t-\Delta t}} - \frac{1}{h^+} \right) \qquad (8)$$

$$\omega^- = q \frac{h^+}{4} \left(\frac{1}{h^- + h^+ - h^{t-\Delta t}} - \frac{1}{h^+} \right) \qquad (9)$$

$$\widehat{\omega}_k = \frac{\iint (\max (0, \omega^+) - \max (0, \omega^-))}{\iint H} \qquad (10)$$

$$\Delta u = u^{t-\Delta t}_k - u^{t-\Delta t}_{k+1} \qquad (11)$$

$$\Delta v = v^{t-\Delta t}_k - v^{t-\Delta t}_{k+1} \qquad (12)$$

$$\tau_k^x = \begin{cases} \tau_w^x & \text{for } k = 0 \\ C_k \rho_o \Delta u \sqrt{(\Delta u)^2 + \left(\overline{(\overline{\Delta v})^y}^x \right)^2} & \text{for } k = 1 \ldots n-1 \\ C_b \rho_o u \sqrt{(u^{t-\Delta t})^2 + \left(\overline{(\overline{v^{t-\Delta t}})^y}^x \right)^2} & \text{for } k = n \end{cases} \quad (13)$$

$$\tau_k^y = \begin{cases} \tau_w^y & \text{for } k = 0 \\ C_k \rho_o \Delta v \sqrt{(\Delta v)^2 + \left(\overline{(\overline{\Delta u})^x}^y \right)^2} & \text{for } k = 1 \ldots n-1 \\ C_b \rho_o v^{t-\Delta t} \sqrt{(v^{t-\Delta t})^2 + \left(\overline{(\overline{u^{t-\Delta t}})^x}^y \right)^2} & \text{for } k = n \end{cases}$$

$$\widehat{H}_k = \text{constant}. \quad (14)$$

Here, $\vec{V} = (U,V), u = U/\overline{h}^x, v = V/\overline{h}^y$, and the layer index k and the centered time t apply to all fields unless otherwise noted.

For two layers equations (3) through (14) are identical to those in Hurlburt and Thompson (1980), except for hydromixing and the pressure-gradient term. The original pressure-gradient term involved the free-surface deviation, η, and the upper layer thickness, h_1, whereas now the layer thickness deviations, $(h_1 - H_1)$ and $(h_2 - H_2)$, are used. These two forms are interchangeable, since $\eta = (h_1 - H_1) - (h_2 - H_2)$ and H_1 is constant, but layer thickness deviations are prognostic fields in the Navy model; hence, it is more natural to use them directly.

Only the pressure-gradient term in the momentum equation and the mass-divergence term in the continuity equation have been made implicit; i.e., this is a semi-implicit formulation of the equations that treats the linear part of the gravity waves implicitly. It is unconditionally stable, provided the constants $\widehat{H}_k$ are such that the explicit part of the pressure-gradient term always acts to slow the gravity waves. The model requires $\widehat{H}_k$ to be greater than h_k, which guarantees unconditional stability.

The linear CFL limit (Courant et al., 1928) on the time step is

$$\Delta t \leq 1/\sqrt{\left(\frac{u_{\max}}{\Delta x}\right)^2 + \left(\frac{v_{\max}}{\Delta y}\right)^2 + f^2} \qquad (15)$$

and the actual time step is typically between 90% and 95% of this limit.

Expressing the n continuity equations, one for each layer, as a single n-element vector equation, we obtain

$$\begin{bmatrix} h_1^{t+\Delta t} \\ \vdots \\ h_n^{t+\Delta t} \end{bmatrix} = \begin{bmatrix} h_1^{\dagger} \\ \vdots \\ h_n^{\dagger} \end{bmatrix} + (\Delta t)^2 \begin{bmatrix} \hat{H}_1 & & \\ & \ddots & \\ & & \hat{H}_n \end{bmatrix} G \begin{bmatrix} \delta^2 & & \\ & \ddots & \\ & & \delta^2 \end{bmatrix} \begin{bmatrix} h_1^{t+\Delta t} \\ \vdots \\ h_n^{t+\Delta t} \end{bmatrix}, \qquad (16)$$

where $\delta^2 = \delta_x \delta_x + \delta_y \delta_y$, and $h_k^{\dagger}$ contains all the terms at time levels t and $t - \Delta t$.

Now, a real eigenmatrix X and eigenvalues λ_k^2 exist, such that

$$\begin{bmatrix} \hat{H}_1 & & \\ & \ddots & \\ & & \hat{H}_n \end{bmatrix} G = X \begin{bmatrix} \lambda_1^2 & & \\ & \ddots & \\ & & \lambda_n^2 \end{bmatrix} X^{-1}. \qquad (17)$$

So,

$$\begin{bmatrix} \delta^2 - 1/(\lambda_1 \Delta t)^2 & & \\ & \ddots & \\ & & \delta^2 - 1/(\lambda_n \Delta t)^2 \end{bmatrix} \begin{bmatrix} \tilde{h}_1 \\ \vdots \\ \tilde{h}_n \end{bmatrix} = -X^{-1} \begin{bmatrix} h_1^{\dagger} \\ \vdots \\ h_n^{\dagger} \end{bmatrix}$$

$$\begin{bmatrix} h_1^{t+\Delta t} \\ \vdots \\ h_n^{t+\Delta t} \end{bmatrix} = X^{-1} \begin{bmatrix} \tilde{h}_1 \\ \vdots \\ \tilde{h}_n \end{bmatrix}. \qquad (18)$$

The semi-implicit continuity equation in real space consists of n-coupled elliptic partial differential equations. By converting to modal space, these are decoupled into n independent two-dimensional Helmholtz equations. The decoupling gives rise to Helmholtz equations because $\widehat{H}_k$ and G_{kl} (and, therefore, X and λ_k) are constants.

The time differencing is leapfrog, but an Heun predictor-corrector difference (Roache, 1976) is used for start and restart. Every so often, typically every 100 to 300 time steps, the solution for at least three adjacent time steps is averaged to exactly filter $2\Delta t$ time splitting, and the model is restarted.

2.3 Boundary Conditions

On the C-grid: zonal boundary sections pass through V grid points, meridional sections pass through U grid points, and diagonal boundary sections pass through both U and V points. In all cases the boundary is exactly $\Delta x/2$ or $\Delta y/2$ from the nearest h grid point. So the coastline is uniquely defined by a map indicating which h grid nodes are sea and which are land. See the appendix for details of the grid used by the model.

Except at inflow and outflow boundary ports, the walls are rigid and the no-slip condition is prescribed on the tangential flow. These boundary conditions are implemented in the model by setting all velocity and transport components that lie on the boundary to zero, and setting all components that lie one-half grid spacing on the land side of the boundary equal to minus those that are one-half grid spacing on the sea side of the boundary. If a U land point has U sea points directly to its north and south, or if a V land point has V sea points directly to its east and west, then the boundary must pass through the land point. At a port setup for inflow only, the transport $\vec{V}_k$, or velocity $\vec{v}_k$, are external forcing fields. The flow at a port setup for outflow is predicted in three steps.

First, a modified Orlanski (1976) radiation condition is used. Consider, for example, a port on the northern boundary of the region. Then, for each component of transport,

$$q_B^{t+\Delta t} = \left(\left(1 - \frac{c\Delta t}{\Delta y} \right) q_B^{t-\Delta t} + \frac{2c\Delta t}{\Delta y} q_{B-1}^{t} \right) \Big/ \left(1 + \frac{c\Delta t}{\Delta y} \right)$$

$$c = \min(\Delta y/\Delta t, \max(c_k, \bar{v}_k)), \tag{19}$$

where B refers to the outflow boundary and $B-1$ to one grid point interior to the boundary, $\bar{v}_k$ is a reference outflow speed that is usually set to the average inflow speed at the inflow ports, and the phase speed, c_k is determined locally for each wave mode. There are several ways to determine the local phase speed, c_k, but the simplest scheme, with $c_k = \bar{v}_k$, is often very effective. Overall, this boundary condition always moves information from the interior toward, and normal to, the open boundary.

Second, a linear implicit drag is an option that may be applied at all points on the port where inflow is predicted. This option prevents the development of any unrealistically large recirculation at the open boundary by applying a "brake" on the inflow component of the recirculation. The e-folding time scale of the drag is chosen to be sufficiently long to allow waves and eddies to migrate out of the region.

Third, the velocity across each outflow port in a layer is uniformly increased or decreased such that the total inflow mass transport, from all inflow ports in that layer, is matched by the total outflow mass transport. This hard mass constraint, time step by time step, on inflow and outflow does not allow for temporary mass storage in the region, and it can lead to problems when spinning up a model from rest. However, it allows the use of excess mass as a debugging tool (since there should not be any net change in mass with this scheme).

To solve the Helmholtz equations for h, we require boundary values for U and V at the new time level. Since interior U and V values are not available until after the new h is known, some boundary conditions on U and V that involve interior values at the new time level could not be used in a semi-implicit model. However, simple boundary conditions of this form, such as those at a free-slip boundary, do not cause any difficulty. In the present model at a solid, no-slip boundary, U and V are both zero for all time; at an inflow port, they are prescribed; and at an outflow port, they depend on interior values from previous time steps only. So in all cases the required boundary values are available when the Helmholtz equation is solved. Note that the value of h cannot be prescribed at an open boundary in this model.

2.4 External Forcing Input

The allowed external forcing fields for the model are bathymetry, wind stress, and inflow boundary, velocity, or transport. All of these forcing fields, except for bathymetry, are optional and can be omitted from a given model run.

Bathymetry is defined on the same grid as h, and it is usually read-in from a file at the beginning of the model run. It must be sufficiently deep to be always below the lowest layer interface, but is otherwise arbitrary. However, it is advisable to smooth out any $2\Delta x$ or $2\Delta y$ components that are present before using a bathymetry field in the model. The bathymetry field is also used to define the model coastline. If a point has a positive bathymetric value, then it is taken as sea; otherwise, it is a land point. Any land-sea geometry is allowed; there is no limit on the number of islands in the geometry, and single-point islands are allowed. Since the bathymetry file also defines the coastline, it must be present. However, in reduced gravity models it has no other effect, and in finite-depth models the amplitude of the topography can be specified. An amplitude of zero corresponds to a flat-bottom case, and an amplitude of one corresponds to the topography exactly as input. Any amplitude may be used, but typically the bathymetry might be defined to reach the surface, and an amplitude slightly less than one would be used to ensure that the actual model bathymetry always remained below the lowest interface.

The wind stress fields are defined on the U and V grids. Wind stresses are usually read-in from a file, or files, during the model run. The time

intervals between wind input are arbitrary and can change from one wind record to the next. At any given time step the model wind stress is formed by a linear interpolation of the nearest input wind stress before that time and the nearest input wind stress after that time. Since the scale of wind features is usually far larger than the scale of oceanic features, only one out of every two wind stress values is input and saved in each direction, i.e., only one-fourth of the points are in the wind-stress file. See the appendix for more details of the wind grid. The wind-stress values at the remaining three-fourths of the points are obtained by linear interpolation in space. Wind fields must be converted to wind stresses at the surface before they are input to the model. If a more sophisticated time interpolation scheme (than the linear interpolation used by the model) is required, interpolated wind stress fields are included in the data file between the times that actual winds are available.

At an inflow boundary in any layer, the inflow angle and either the velocity magnitude and profile or the transport magnitude and profile can be specified. These quantities are not allowed to change with time, except on restart when a new inflow angle and new magnitudes can be specified, and the model will spin up from the old to the new values. At the start of the run the magnitudes spin up from the initial state to the specified values. Outflow boundaries use a radiation condition and do not use any specified data.

3.0 Model Code

3.1 Programming Language

The ocean model is written entirely in the American National Standard Institute's standard FORTRAN 77, with the exception of the following extensions:

- NAMELIST I/O (input/output) is used to read-in model parameters.
- DATA statements within normal subroutines are used to initialize variables in some named COMMON areas.
- Some I/O routines are machine-dependent, and may include non-standard FORTRAN features on some machines, e.g., LOGICAL*1 or BYTE data types might be used.

All the machine-dependent code is accessed via a single subroutine. The reason for using machine-dependent I/O is to allow the data to be machine-independent and compact. The only standard FORTRAN method of producing machine-independent data is formatted I/O, but this procedure is slow and wastes storage (disk) space. With the current scheme, model data generated on one computer can be used later on another computer of a different type, either to produce graphical output or to restart the model and continue to run.

3.2 Use of Third-Party Modules

LINPACK and EISPACK are the only third-party modules called by the model. These modules solve simultaneous linear equation and eigenvalue problems, respectively. Both are in the public domain, and highly optimized versions are often available in the standard math library on supercomputers.

The Helmholtz equations generated by the semi-implicit time scheme are solved using a locally written standard FORTRAN 77 package that has been highly optimized for use on vector supercomputers. It uses a fast direct solver for rectangular regions (Swarztrauber, 1977) and the

capacitance matrix technique for general regions (Buzbee et al., 1971; Wallcraft, 1980). The fast direct solver includes an efficient, standard FORTRAN 77 package for fast Fourier transforms of length 4×2^2 or 5×2^2 or 6×2^2 (Moore, 1989).

Graphical output is produced as a postprocessing step separate from running the ocean model. The National Center for Atmospheric Research graphics package, together with a level 2B implementation of the Graphics Kernal System (GKS) is used as the basis for all graphical output. GKS is an international standard for two-dimensional graphics and is widely available—at least six commercial implementations are available for Digital's VAX computer. Since the model data is machine-independent, it can be copied to any suitable workstation or computer to produce the graphics.

3.3 Run Interruption

At user-specified intervals the model checks that the prognostic fields are within reasonable ranges, and it will terminate if they are not. This inspection is useful on such computers as the Cray, which have very large exponent ranges and take a long time to overflow if the model blows up. Standard interactive debuggers are not usually very useful when a model overflows, because the problem often occurs much earlier. The usual procedure in such a case would be to restart from the last available restart data set and frequently write out fields for off-line graphical display.

At another user-specified interval a complete data set suitable for restarting the model is output. An internal check ensures that this interval corresponds to no more than a set amount, typically 30 minutes, of central processing time. If the model is interrupted for any reason, then it can be restarted at the time of the latest restart data set. The restart involves changing the start date of the run, specifying the correct files to read the restart data from, and resubmitting the job.

After a restart data set is output, the amount of central processing time the job has left is checked, and the program will terminate if the time is not sufficient to reach the next restart dump. This procedure ensures that enough time is left after the run to save files, etc. This process is particularly important on computers that delete local files at the end of a run.

3.4 Implementation

The model has been run on the following computer systems:

- Cray X-MP under COS, using CFT and CFT77 compilers.
- Cray 2 under UNICOS, using the CFT77 compiler.
- Cray Y-MP under UNICOS, using the CFT77 compiler.
- Cyber 205 under VSOS, using the FTN200 compiler and VAST, VAST II, or KAP precompiler. A precompiler is essential for efficiency on the 205.
- Convex C-1 under UNIX, using the *fc* compiler.
- Alliant FX/80 under Concentrix (UNIX), using the FORTRAN compiler.
- VAX (μVAX II, 11/780, 11/785, 8650, and 8800) under VMS, using the VMS FORTRAN compiler.
- Sun 4/110 under SunOS (UNIX), using Sun FORTRAN.
- Compaq DESKPRO 386/20 under Interactive System's 386/ix (UNIX System V/386), using Microway's NDP FORTRAN 386.

All the required compiler directives are present in the code for each of the different vectorizing compilers. The model contains internal documentation detailing any minor modifications to the code required on each machine. These modifications are usually concerned with OPEN, since it is difficult to make this statement completely machine-independent. On almost all of these machines the model runs in single precision, which contains 32 bits on everything except the Crays. The semi-implicit model must run in 64-bit mode on the Cyber 205 because it has a particularly inaccurate implementation of 32-bit arithmetic. The precision of the model is determined by an IMPLICIT statement at the head of each routine.

Most of the work required to implement the model on a new computer system is in writing the machine-dependent routines for machine-independent I/O and in porting the Helmholtz equation package. Implementing the I/O routines on a new machine requires knowledge of how to efficiently handle data that are smaller than the usual machine word length. The existing Sun FORTRAN version will work on most machines that run UNIX, but it would probably have to be modified to attain maximum efficiency on a new UNIX-based vector or parallel computer. The Helmholtz equation package is written in standard FORTRAN 77, and test programs are available to check that it is producing correct results. The package is designed to be automatically vectorized by a wide range of compilers, but additional optimization (extra compiler directives, for example) would probably be required to attain full efficiency on a new vector or parallel computer. The Helmholtz equation package is treated as a "black box" by the ocean model, so it could be replaced by any other Helmholtz equation package that includes the capability to solve problems with homogeneous Neumann boundary conditions located halfway between grid points on the h-grid.

4.0 Using the Model

4.1 Overview

The model code contains internal documentation that fully describes the various user-specified model parameters and data sets. The details of this information will not be reproduced here, since it is likely to change slightly with each new release of the model. The internal documentation will always be current, so this user's guide should be used only to gain a general idea of how the model works. Some of the internal documentation applies only to the thermodynamic version of the model, which is still under development and has not been released for general use.

4.2 The Model Label

Each experiment has a user-supplied label associated with it. This label appears in all data files and on all the standard graphical products supplied with the model. The label consists of a five-digit integer followed by a four-digit integer. The five-digit integer, together with the number of active layers, should uniquely identify the region and the model used for the experiment. It is set by a PARAMETER statement in the model code, so experiments run from the same code will definitely have the same five-digit identifier. The second, four-digit integer should uniquely identify the experiment, so it is set at run time.

The five digit integer has the following form:

- a two-digit region identification number
- a one-digit region version number
- a one-digit model type number
  - 1 for explicit hydrodynamic models
  - 3 for semi-implicit hydrodynamic models
- a one-digit model "geometry" number
  - 0 for reduced gravity models on a beta-plane
  - 1 for reduced gravity models on a sphere
  - 2 for finite depth models on a beta-plane
  - 3 for finite depth models on a sphere

The four-digit integer has the following form:

- a three-digit experiment identification number
- a one-digit subexperiment identification number

The four-digit integer is divided by 10 to give the overall experiment number; for example, the first experiment would probably be called 1.0, so the integer would be 0010. By convention each experiment started from rest has a subexperiment identifier of 0, and the other subexperiment identifiers are reserved for experiments restarted from that experiment with different model parameters or different model forcing.

For example, at NOARL the region identification number of 11 is used for world ocean regions. Currently, six versions are available: 111, 112, 113, 114, 115, and 116, all of which have differing north-south extents and differing grid resolutions. So from an experiment label, such as 11611, 0134, we can immediately tell that the experiment is for the world's oceans on our latest grid, that the experiment is hydrodynamic, and that it uses spherical coordinates. Since the experiment is 13.4, we also know that it is a variation of experiment 13.0; for example, 13.0 might have been run for 50 years from rest using Hellermann-Rosenstein (1983) climatological winds, and experiment 13.4 might have been restarted from the 50th year of 13.0 with some other wind set.

4.3 Model Setup

4.3.1 On a New Ocean Basin

The following steps are taken to set up the model on a new ocean region.

- Select the model grid spacing, the region extent, and the initial vertical structure. These areas define what kind of model to use (spherical versus beta-plane, reduced gravity versus finite depth, grid size, number of layers).
- Always start from the Gulf of Mexico code as originally distributed (with LABEL1=990).
- Modify the PARAMETERs *IH, JH, AND KH throughout.*
- Define the PARAMETER LABEL1 to uniquely identify the region/model combination (see above).
- Create a new topography file and possibly modify PARAMETERs LXX, IXX, IYY in the subroutine XXLND.
- Modify many PARAMETERs in subroutine CHSLVX or SHSLVX to set up the Helmholtz equation solver for the new region, and modify all the entries in MHSLV to call either CHSLV or SHSLV as required.
- Modify XXPOR (ZP101, ZP001, etc.) to implement the required ports. Use a dummy version of XXPOR if there is no port forcing.
- Possibly define a new analytic wind stress function in subroutine XXAWND.
- Possibly generate one or more wind stress files.

4.3.2 On a New Type of Computer

The following steps are taken to implement the model code on a new computer:

- Use a FORTRAN 77 compiler.
- Use the NAMELIST statement to read-in model parameters; if NAMELIST is not available, use READ (s,*).
- Develop versions of the history file I/O routines (XHHIS, ZHHIS, ZHIOXX, ZHTXTOX) that read and write history fields in exactly the correct manner, i.e., as 24-bit, 2's complement integers.
- Reduce the PARAMETER NHTMAX in subroutine XHHIS appropriately if the history file unit numbers must be limited to less than 65 . . . 80.
- Test against an existing benchmark run on another machine if possible. Otherwise, check that mass is conserved by running in single and double precision and comparing "mean height anomalies," which should be smaller by a factor of about 10^8 in double precision. The U, V, and h fields should closely agree in the two cases.

5.0 Summary

This report is a users guide to the Navy's hydrodynamic (isopycnal) nonlinear primitive equation layered ocean circulation model. The model retains the free surface and uses a semi-implicit time scheme that treats all gravity waves implicitly. It can handle full-scale bottom topography, provided it is confined to the lowest layer, and an arbitrary coastline geometry.

The model has been in use at NOARL for more than 10 years for simulations of the ocean circulation in the Gulf of Mexico, The Caribbean Sea, the Alboran Sea, the western Mediterranean Sea, the Indian Ocean, the western North Atlantic, the North Pacific Ocean, and the global ocean. The model code is being made available to the ocean modeling community in conjunction with the issuing of this report.

The vertically integrated equations of motion and their finite difference discretization on a C-grid have been presented, as has a description of the semi-implicit time scheme, the boundary conditions, and the external forcing.

The model code contains internal documentation that fully describes the user specified model parameters and data sets. This report also contains general information about how to use the model, in particular, how to set it up for a new ocean region and how to port it to a new computer system.

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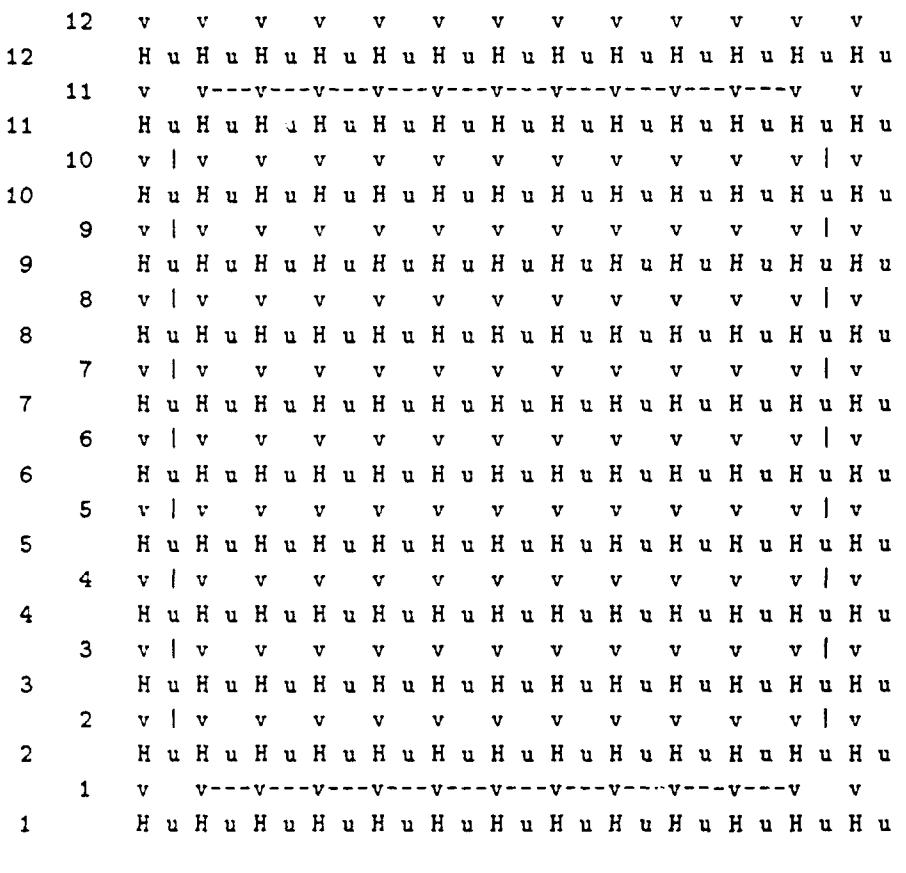
Appendix
The C-Grid

The following figures show the relative position of the U, V and h staggered grids in the C-grid scheme used by the ocean model. They also show how grid points are numbered within two-dimensional arrays in the model. The size of the mesh array is chosen to just cover the model region, but because the array is rectangular a large fraction of the array might represent "land" for some regions. In this case, the region is a simple rectangle $12\Delta x$ by $11\Delta y$, so all mesh arrays are dimensioned 13 by 12 (i.e., IH = 13 and JH = 12), and very little of the array is "land." The sides of the region are on the U grid, at I = 1 and I = 12, and the top and bottom are on the V grid at J = 1 and J = 11. If the region has solid walls, these U and V points will be set to zero as part of the no-slip boundary condition. On the h grid all the nodes in rows J = 1 and J = 12 and in columns I = 1 and I = 13 are outside the region. They are never used by the model, but would be set to negative values in the topography array to indicate that they are over land. All other nodes in the topography array would have positive values representing the ocean depth at that point. On the U grid all nodes in column I = 13 are outside the region and are never used. All nodes in rows J = 1 and J = 12 are one-half grid point outside the region and, assuming the boundary is a solid wall, these will be set equal to minus the corresponding nodes in rows J = 2 and J = 11 as part of the no-slip boundary condition. On the V grid all nodes in row J = 12 are outside the region and are never used. All nodes in columns I = 1 and I = 13 are one-half grid point outside the region, and assuming the boundary is a solid wall, these will be set equal to minus the corresponding nodes in columns I = 2 and I = 12 as part of the no-slip boundary condition.

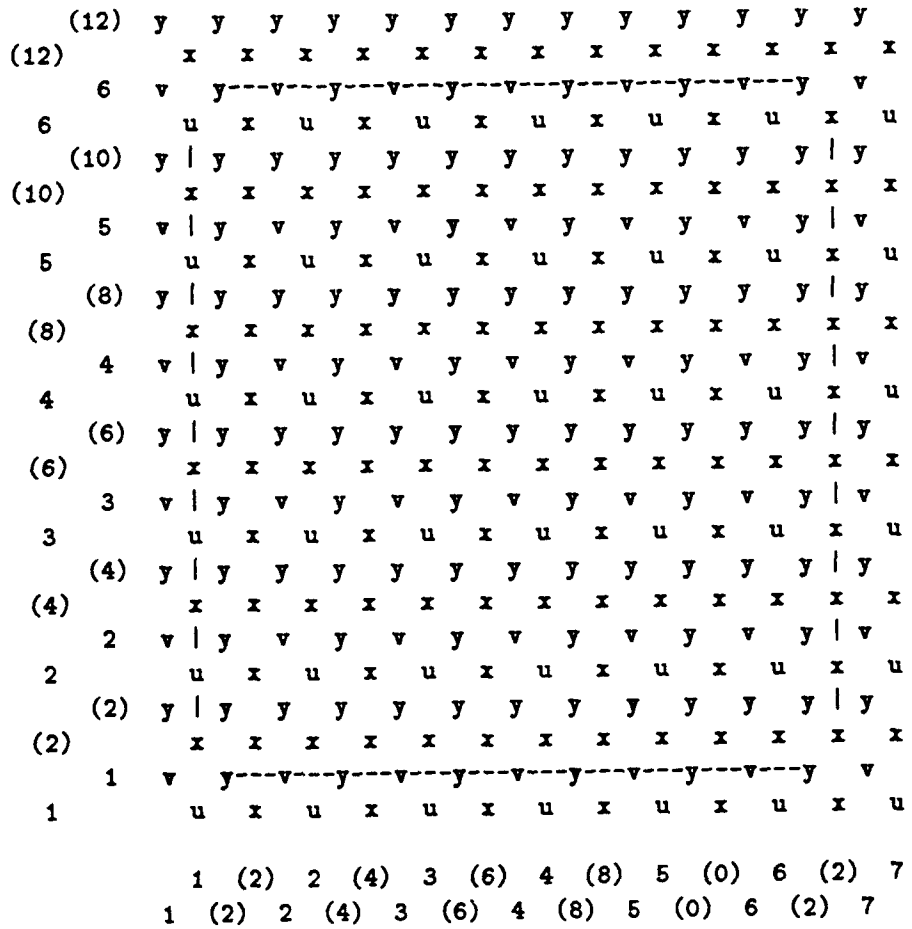
Wind stress components are stored only at every second point, as is indicated in the second figure. Wind stresses must be defined at all points on these subsampled grids because the values over land may be used in the interpolation for a sea point.

IH = 13 and JH = 12



U-V-H Staggered Grid.

IH = 13 and JH = 12, IW = 7 and JW = 6



Staggered wind grid.

The wind gridpoints are u, v and the nonwind gridpoints are x, y.

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Woods Hole MA 02543
Attn: Director

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. Agency Use Only *(Leave blank).*	2. Report Date.	3. Report Type and Dates Covered.
	December 1991	Final

4. Title and Subtitle.

The Navy Layered Ocean Model Users Guide

5. Funding Numbers.

Program Element No.	0602435N
Project No.	03584
Task No.	803
Accession No.	DN259116

6. Author(s).

Alan J. Wallcraft

7. Performing Organization Name(s) and Address(es).

Planning Systems, Inc.
115 Christian Lane
Slidell, Louisiana 70458

8. Performing Organization Report Number.

NOARL Report 35

9. Sponsoring/Monitoring Agency Name(s) and Address(es).

10. Sponsoring/Monitoring Agency Report Number.

11. Supplementary Notes.

Prepared for Ocean Sensing and Prediction Division, Ocean Science Directorate,
Contract # N00014-89-C-6002

12a. Distribution/Availability Statement.

Approved for public release; distribution is unlimited. Naval Oceanographic and Atmospheric Research Laboratory, Stennis Space Center, Mississippi 39529-5004.

12b. Distribution Code.

13. Abstract *(Maximum 200 words).*

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The model has been in use at the Naval Oceanographic and Atmospheric Research Laboratory for more than 10 years for simulations of the ocean circulation in the Gulf of Mexico, the Caribbean Sea, the Alboran Sea, the western Mediterranean Sea, and the global oceans. In conjunction with the issuance of this report, the model code is being made available to the ocean modeling community.

The vertically integrated equations of motion and their finite difference discretization on a C-grid is presented, as is a description on the semi-implicit time scheme, the boundary conditions, and the external forcing.

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14. Subject Terms.

thermodynamic ocean model, world ocean, numerical model, Gulf of Mexico, ocean circulation model, energetics

15. Number of Pages. 24

16. Price Code.

17. Security Classification of Report.	18. Security Classification of This Page.	19. Security Classification of Abstract.	20. Limitation of Abstract.
Unclassified	Unclassified	Unclassified	None